Issues in Ecology

Number 6, Spring 2000

Published by the Ecological Society of America

Applying Ecological Principles to Management of the U.S. National Forests

Applying Ecological Principles to Management of the U.S. National Forests

SUMMARY

The U.S. National Forest System is a diverse and unique resource that must be managed within the context of competing and shifting social expectations. The policies under which the system operates have changed over the century, along with the values society places on wood production, wilderness protection, recreation, and biodiversity conservation. Proposals for major changes in the management of the National Forests are once again being debated. The consensus among forest ecologists is that all forests, despite their complexity and variability, should be managed as ecosystems. Sustainable forest management practices must be based on an understanding of how natural forest ecosystems work.

We have identified major ecological considerations that should be incorporated in sound forest management policy and their potential impacts on current practice:

- Maintenance of soil quality and nutrient stocks that hold the key to current and future forest productivity may necessitate adjusting timber harvest rates and leaving more large woody debris on cutover sites.
- Protection of water quality and yield and prevention of flooding and landslides call for greater attention to the negative impacts of logging roads and the value of undisturbed buffer zones along streams and rivers.
- Conservation of forest biodiversity will often require reducing forest fragmentation by clearcuts and roads, avoiding harvest in vulnerable areas such as hardwood or old growth stands and riparian zones, and restoring natural structural complexity to cutover sites.
- Planning at the landscape level is needed to address ecological concerns such as biodiversity, water flows, and forest fragmentation. Repeated overcutting of National Forests lands in the past has been linked to lack of planning at the landscape scale.
- Increasing pressures on forests due to human population growth and global change oblige land managers to be alert for climate-related stresses as well as damage from ground-level ozone, acid rain, and acidification of soils and watersheds.

This panel also analyzed the ecological assumptions, both explicit and implicit, that underlie a number of current proposals for changes in National Forest management. Key assumptions in some of these proposals are unsupported or directly contradicted by current knowledge of forest ecology. We are confident that:

- Despite natural disturbance and successional change, forest reserves are much more likely to sustain the full biological diversity of forests than lands managed primarily for timber production.
- No evidence supports the view that natural forests or reserves are more vulnerable to disturbances such as wildfire, windthrow, and pests than intensively managed forests. Indeed, there is evidence natural systems may be more resistant in many cases.
- Traditional beliefs that timber harvesting can duplicate and fully substitute for the ecological effects of natural disturbance are incorrect, although newer techniques such as retaining trees and large woody debris on harvest sites can more closely mimic natural processes.
- There is no scientific basis for asserting that silvicultural practices can create forests that are ecologically equivalent to natural old-growth forests, although we can certainly use our understanding of forest ecology to help restore managed forests to more natural conditions.
- Proposals to ban all timber harvesting on National Forests would leave managers without a valuable tool that can be used selectively to restore early successional habitat, reduce fuel loads, and contain pest and pathogen outbreaks in some forests.

Creativity is needed in designing forest management policies for the future, but simple solutions are almost never adequate for sustaining a complex system that must fulfill diverse expectations. Sustainable management policies must make full use of current ecological knowledge. The goal of our policy efforts today should be to design forest management practices that assure the value of our forest resources for future generations.

Applying Ecological Principles to Management of the U.S. National Forests

by John Aber*, Norman Christensen, Ivan Fernandez, Jerry Franklin, Lori Hidinger, Malcolm Hunter, James MacMahon, David Mladenoff, John Pastor, David Perry, Ron Slangen, Helga van Miegroet

INTRODUCTION

The U.S. National Forest System is a diverse and unique resource, encompassing approximately 192 million acres and representing most of the continent's major forest types. The system itself is entirely a creation of twentieth century political and social forces, and society's expectations for it have changed repeatedly over the century. As the values society places on timber production, wilderness protection, recreation, and conservation of biological diversity have shifted, so have the policy directives under which the system operates.

The various legislative mandates under which the National Forest System has operated began with The Organic Administration Act of 1897 that established the first policy for national forest use and management. The act gave the President authority to establish national forests on public lands in order to "improve and protect the forest within boundaries, or for the purpose of security, favorable conditions of waterflows, and to furnish a continuous supply of timber for the use and necessities of citizens of the United States" (Fedkiw 1999). The 1960 Multiple Use Sustained Yield Act extended this by specifying five things that were to be sustained on public lands—timber, fish and wildlife, outdoor recreation, range and fodder, and watersheds (Wiersum 1995). The National Forests Management Act of 1976 in turn specified that this policy of multiple use be incorporated into a mandated planning process.

Today we are experiencing another period of shifting values as well as conflicting proposals for major changes in the management of the National Forest System. Some segments of society propose to increase forest harvesting dramatically while others want to eliminate harvesting altogether (e.g., Oliver et al. 1997, McKinney 1999). Policies regarding the role of natural disturbances such as fire are also under review. Recently, the U.S. Forest Service began reviewing its mission based on the recommendations of the Committee of Scientists Report (1999) commissioned by the Secretary of Agriculture. This committee of 13 academics and professionals concluded that ecological sustainability and pubic ownership and participation are key guiding principles for managing the National Forests.

Behind this changing human backdrop, the forests themselves are also dynamic, constantly changing in response to stress, disturbance, and climate, yet always constrained by their underlying physical, chemical, and biological processes. The stresses on forested ecosystems and the plant and animal species they harbor are continually increasing because of human population growth, pollution, climate change, and other threats (Figure 1).

The key to responsible forest management is understanding how the natural systems work and developing management prescriptions consistent with that knowledge. When political pressures are strong, however, it is all too easy for land managers and decision makers to lose sight of the ex-

Photo by Jerry Franklin.

Figure 1 - Continuous clearcutting of forests can create major environmental problems, such as in maintaining biological diversity and providing for well-regulated, high-quality streamflow. Private forest lands, western Washington state.

* Authors in alphabetical order.

tent and value of the knowledge base that has been developed on forest ecosystem dynamics and response to disturbance.

The purpose of this report is to outline key ecological considerations that should underlie sound forest management. The complexity and variability of forest ecosystems throughout the United States make it difficult to formulate ecological principles that apply uniformly to all. Yet there is consensus among forest ecologists about one generalization: All forests should be regarded and managed as ecosystems – ecosystems that represent a variety of resources and values for different forest users.

In the first section of this report, we discuss ecological considerations for forest management in five broad categories: 1) soil and nutrient cycles, 2) hydrology, 3) biodiversity, 4) landscape level issues, and 5) global change. In the second section of the report, we examine and critique some of the ecological assumptions that explicitly or implicitly underlie several current forest policy proposals. In particular, we analyze acceptable or desirable levels of direct human manipulation and use of federal forests based on current ecological understanding. Rather than presenting a comprehensive review of the literature, we discuss principles that are generally accepted among ecological scientists. (An excellent review of the literature on the scientific basis of forestry was presented by David Perry (1998) in the *Annual Review of Ecology and Systematics*.)

A single overarching principle sets the context for this report: The National Forest System should be viewed as a multifaceted resource of continuing value, and current management policies and practices should not devalue the resource for future generations. Any set of management practices should therefore be sustainable for the indefinite future.

ECOLOGICAL CONSIDERATIONS IN FOREST MANAGEMENT

From the early days of its creation, the U.S. Forest Service has had two primary goals: to support local industry and to protect and sustain watersheds. Over time, new laws and policies have expanded the agency's mission to include recreation, biodiversity conservation, and maintenance of soil quality and natural processes. We examine here five broad categories of ecological considerations that should go into management practices designed to fulfill this complex mission and to sustain forest resources into the future: (1) soil and nutrient cycles; (2) hydrology; (3) biodiversity; (4) landscape level issues; and (5) global change.

SOIL AND NUTRIENT CYCLES

Soil quality is central to sustainable forest management because it defines the current and future productivity of the land and promotes the health of its plant and animal communities (Doran and Parkin 1994). A great deal is known about the importance of soil quality for the functioning of forest ecosystems and also how management practices affect soil quality (eg., Cole 1995 and Perry and Rose 1998). Although very little research has been published on systems for evaluating or monitoring soil quality, defining it and initiating programs to evaluate its maintenance and promotion are central to achieving demonstrable sustainability in our National Forests. The ability to define and measure soil quality is important for applications at a number of scales, from monitoring soil compaction and nutrient supply at specific sites to addressing global concerns about the amount of carbon sequestered in the wood of the world's forests.

What is soil?

Soil is a unique and complex blend of minerals, living organisms, and the organic products of organisms. It provides habitat and physical support as well as sustenance for a teeming array of creatures, from bacteria and fungi to mites, earthworms and plants. The soil and its living community store and cycle nutrients, regulate water flows, and also filter, buffer, degrade, immobilize, or detoxify a myriad organic and inorganic materials (USDA NRCS 1996).

Healthy soil performs three critical ecological functions in forested ecosystems. One is nutrient cycling, a process carried out by invertebrates and microbes that decompose dead organic matter and release vital plant nutrients such as nitrogen and phosphorus for reuse. This activity accounts for the majority of nutrients taken up by plants in mature forests. Second, healthy soil enables a forest to maintain some productivity (tree growth) during periods of shortage, especially drought. Third, healthy soil is capable of retaining fertility and thereby facilitating plant recovery following disturbances such as fire or timber harvesting. The latter capability quickly degrades, however, when plant cover is removed and the soil is left bare (Perry 1998).

Soil Structure and Organic Matter

A significant concern in the maintenance of forest soil quality is assuring the replenishment of surface and soil organic matter and avoiding compaction of the soil (Powers et al. 1990). Soil organic matter includes highly decomposed material called humus, less decomposed leaf litter and other detritus, and large woody debris such as branches and stems. This organic material stores nutrients and water and supplies the carbon to nourish the myriad belowground organisms, many of which perform the critical tasks of releasing the mineral nutrients necessary for continued plant growth.

As long as plant communities regrow vigorously after timber harvesting, losses of soil carbon derived from fine litter will be replenished. Regrowth, of course, depends on the status of soil nutrients, soil carbon, and soil biology after harvest.

More problematic is the replenishment of those components of soil carbon that are derived from large woody debris, especially tree stems (Figure 2; Harmon et al. 1986). The practice of leaving tree stems on site is not common in

intensive forestry today, and in fact, doing so has been seen as a waste. The question of how many trees to leave to sustain soil quality is not easily answered at present and will require further research on the ecological functions of large dead wood. Yet retaining trees on site as future sources of large woody debris must be a major component of sustainable forest management.

Nutrient Cycling

Another major factor in sustaining soil quality is maintaining pools of essential plant nutrients and assuring these are steadily available in forms that plants can use. Undisturbed forests seldom experience significant losses of nutrient stocks. Thus an important element in sustainable forestry is taking care that management practices do not result in long-term reductions in a forest's nutrient capital or in the long-term availability of those nutrients to plants.

Until recently, nitrogen has been considered the most important nutrient limiting tree growth in temperate and boreal forests, and by far the majority of research has focused on nitrogen losses associated with timber harvest and site preparation (Johnson 1992). Losses from a harvested site take three forms: removal of the nitrogen contained in the harvested wood, nitrogen leached and eroded from disturbed soil, and nitrogen volatilized and lost to the atmosphere during slash burning. The extent and impact of these losses vary depending on numerous site-specific factors such as nitrogen availability and climate and also on management practices (Cole 1995). In the nitrogen-poor forests of the western U.S., for example, losses in wood removal and slash burning far exceed those in leaching, while in more nitrogen-rich eastern forests, leaching losses can be quite high.

Watershed-scale studies and harvesting experiments show that total nitrogen lost from a site after clearcutting varies widely among forest types. Since nitrogen is considered the major nutrient limiting tree growth in most systems, post-harvest losses are regarded as a long-term threat to forest productivity. Nitrogen losses in the form of nitrate leached from soils to streams are especially variable from one forest to another. Elevated nitrate levels in streams following harvest or forest disturbance represent a threat to water quality because nutrient fouling can lead to a wide range of problems from algal blooms, loss of oxygen, and fish kills to degradation of drinking water. In general, forest ecosystems with higher levels of nitrogen mineralization (release of nitrogen from decomposing soil organic matter) have been shown to exhibit higher rates of nitrate production and loss, and these losses are further increased by the removal of trees and corresponding elimination of nitrogen uptake by the trees. (Hibbert 1969, Likens et al. 1970, Hornbeck et al. 1996).

Figure 2 - During the last 30 years it has become apparent that logs and other woody debris fulfill many ecological functions and persist for centuries, as in the case of this giant sequoia log. Note person in red for scale. Photo by Jerry Franklin.

Computer modeling of nutrient requirements for forest growth as well as studies on watersheds and forest ecosystems agree that, in principle, harvesting whole trees and using short intervals between harvests on a site lead to significant reductions in soil nitrogen stocks, nitrogen availability, and productivity. Large losses of phosphorus, calcium, magnesium, potassium, and other nutrients also occur in association with whole-tree harvest and short rotations (Kimmins 1977, Smith et al. 1986, Johnson and Todd 1987). Some practices used to clear logging slash and prepare sites for planting significantly impact soil fertility, especially the use of heavy equipment to push slash and other organic matter into piles, a practice called windrowing (Powers et al. 1990). In a sustainable forest management program, therefore, rates of tree removal and other management activities should be planned according to nutrient budgeting techniques in order to reduce or deter long-term degradation of soil nutrients.

Nitrogen Saturation

Concerns have increased across much of North America and Europe about the overabundance of nitrogen entering forests due to the human-driven buildup of airborne nitrogen. It is now recognized that human activities such as burning of fossil fuels and production of nitrogen fertilizers have effectively doubled the supply of biologically available nitrogen. Thus, research on nitrogen shortages due to tree harvest has been augmented by investigations into the effects of

excess nitrogen availability and consequent nitrate leaching due to increased airborne nitrogen entering forest soils as dry deposition or acid rain (Aber 1992, Fenn et al. 1997).

Increasingly, a phenomenon known as "nitrogen saturation" from atmospheric deposition has been observed in some forest ecosystems where growth is normally limited by the availability of nitrogen. Nitrogen saturation occurs when inputs of nitrogen exceed the rate at which soils, plants, and microbes can use or store it, and the excess is lost to streams, groundwater, or the atmosphere. In the eastern U.S., this saturation has been witnessed in forests at intermediate to high elevations that receive large amounts of nitrogen deposition. In the western U.S., the early stages of nitrogen saturation have been observed in high elevation ecosystems of the Colorado Rockies Front Range. In some areas of the West, however, nitrogen saturation is much more advanced. For example, in mixed conifer forests and chaparral stands surrounding the Los Angeles Basin, nitrogen deposition is so high and has been occurring for so long that these systems have been highly impacted by nitrogen saturation.

Although elevated nitrogen deposition could potentially offset harvesting losses, it is also likely to exacerbate the acidification of soils (Schulze 1989, Federer et al. 1989). As negatively charged nitrates seep away into streams or groundwater, they carry along positively charged minerals such as calcium, magnesium, and potassium. Loss of these alkaline minerals acidifies the soil and decreases its fertility. Forest harvesting and associated nitrate leaching can intensify this chemical imbalance and lead to potentially severe limitations on forest growth. In ecosystems rich in nitrogen, excessive control of early successional vegetation that resprouts following harvest removes an important "biological dam" and may greatly increase leaching of nitrate and other nutrient elements. With the growing prevalence of nitrogen saturation in forest ecosystems, retaining a healthy green cover at all times, either through retention harvests or regrowth of early successional plants (or both), will become increasingly important to conserve soil nutrient capital after logging.

Figure 3 - Deadwood (logs) and other woody debris provide a major contribution to the structure of riparian zones like in this small headland stream. Sequoia-Kings Canyon National Park, CA. Photo by Jerry Franklin.

HYDROLOGY

The headwaters of the nation's largest rivers, which supply much of our fresh water, originate on National Forest land. Cutting of timber in these watersheds raises three concerns: changes in the volume of water flowing to streams, timing of those flows, and water quality, especially sediment loads.

Water Yield and Flooding

Accurate generalizations about the impacts of clearcutting on the volume and timing of stream flows are extremely difficult because of the high variability of such flows, both over time and from one forest system to the next. Because of natural variability in flows, only dramatic impacts of tree removal on stream hydrology are statistically detectable in short-term studies. Decades-long records are often necessary to discern trends, especially in larger basins. Also, a variety of factors from harvest practices to bedrock geology, topography, and climate (whether rain or snow dominates, whether fog-drip from canopies is significant) affect the volume and timing of stream flow.

The clearest effects of harvest on water flows have been obtained from experimentally paired small watersheds (Reiter and Beschta 1995). These watershed studies generally show that clearcutting increases water yield. An exception may be found in foggy regions where tree crowns rake significant water from clouds or fog. In such fog-drip forests, water yields may decline following harvest.

Peak flows are of more concern environmentally and economically because high peak flows can result in damaging floods. Often clearcutting increases peak flows, although that can vary with the extent and rate of logging within a basin, how the logging is carried out, and the extent of the forest road network. Practices such as intensive site preparation, prevention of shrub and grass regrowth on the site, extensive roading, and disruption of streambank and floodplain forests have the greatest likelihood of increasing the magnitude and duration of peak flows and the threat of flooding (Reiter and Beschta 1995). Sustainable forest management should limit such practices in vulnerable watersheds.

Impacts of Logging Roads

Studies in western Oregon demonstrate that clearcutting and roads act synergistically to alter hydrology in a forest (Harr 1976). Removal of trees from a site necessarily reduces water loss to evapotranspiration (evaporation from plant surfaces and transpiration from leaf pores) and also increases snow accumulation and speeds melt since no trees shade the snowpack. As a result, deep-soil water storage increases on cutover sites, and this effect persists for decades until the leaf canopy of deep-rooted trees and shrubs has fully recovered. In poorly drained areas, water tables rise in clearcuts (Burger and Pritchett 1988), sometimes triggering bog formation (Perry 1998).

Roads, on the other hand, cut into hillslopes and allow deep-soil water to surface and run rapidly to streams (Harr et al. 1975). In two watersheds on the H.J. Andrews Experimental Forest in the Oregon Cascades, for instance, peak stream flows were the same on a watershed that was 100 percent clearcut but had no roads and one that was only 25 percent clearcut but had roads (Jones and Grant 1996). For the first five years after harvest, peak flows averaged greater than 50 percent higher than before the cuts, then began to decline. However, 25 years after the harvest, peak flows were still higher by 25 to 40 percent.

Sedimentation, Erosion, and Landslides

The effects of forest management on sedimentation have been easier to demonstrate than effects on water flows because background variability is much less — very little soil is eroded from undisturbed forests. Once again, the best-documented studies come from experimental watersheds, although these are supported by evidence from historical observations and logged and unlogged watershed comparisons.

Sediments associated with forestry come from four primary sources: surface erosion from roads, surface erosion from clearcuts, mass transport during slash burns, and landslides associated either with roads or clearcuts. Studies on the H.J. Andrews Experimental Forest found that landslides, especially from poorly designed roads during major storms, pulsed large amounts of sediment in brief episodes, while surface erosion from roads and clearcuts was more chronic (Swanson et al. 1989). As studies of water flow have shown, roads and clearcuts act synergistically. Eleven years after harvest, suspended sediment lost from a roaded watershed that was 25 percent clearcut averaged 57 times greater than sediment losses in an unroaded, unlogged control watershed. In contrast, a similar watershed that was 100 percent clearcut but unroaded experienced sediment losses averaging 23 times greater than in the undisturbed watershed.

Absolute amounts of erosion from one area do not necessarily extrapolate to others because erosion varies depending on slope steepness, soil, rock type, and snow and rainfall patterns. Areas with large expanses of bare mineral surface, especially in regions where intensive rainstorms are likely, can experience splash erosion as rainfall knocks sediment loose, splash compaction as rain packs down the soil, or gully erosion.

Removal of trees and resulting increases in deep-soil water can threaten the stability of slopes and increase the possibility of landslides. Unless the reduced evapotranspiration caused by clearcutting is accompanied by increased water flow to streams, the result can be wetter soils and decreased soil cohesion. Plant roots also play an important role in slope stability, and management practices that decrease root density or vitality can destabilize slopes and contribute to slope failures, although these may not occur until several years after vegetation removal. The long-term impact of such practices will depend on how quickly the roots of new vegetation expand in relation to the decay of roots from the harvested trees.

In addition, water quality and aquatic systems can be degraded by leaching of nitrate from nitrogen-saturated soils. The primary result of excess nitrogen in forest ecosystems is elevated loss of nitrate to groundwater or surface water. The impacts of increased nitrate leaching to aquatic systems include eutrophication of estuaries and increased toxicity to surface waters. These can pose serious threats to sensitive aquatic organisms, especially fish communities in small streams (Fenn et al. 1998).

Management practices that create ruts or tracks can greatly speed the flow of water across the landscape and thus increase the potential for gully erosion and sediment transport. Buffer strips of undisturbed vegetation along streams and floodplains can be a critical component of forest management because of their capacity to slow such overland flows, allow suspended sediments to settle out, and ultimately reduce siltation of streams. A program of sustainable forest management should embrace such solutions and take care to avoid practices that result in greatly increased or irreversible loading of sediment to rivers and streams.

BIODIVERSITY

The term "biodiversity" encompasses the full variety of life on earth, from genes and species to ecosystems and landscapes, as well as ecological processes that both sustain and are sustained by living things. Both laws and emerging societal values have made forest managers responsible for protecting biodiversity as well as the habitats and processes that maintain it.

The effects of timber harvesting on biodiversity depend on scale, intensity, and method of harvest, as well as how individual animal and plant species respond to harvesting. In general , however, forestry practices affect biodiversity principally by changing the age of a forest, its horizontal and vertical structure, and its species composition. As commonly practiced, forestry structurally simplifies natural landscapes and also adds new elements. Some species increase in numbers while others are jeopardized. While some species may adapt to the changes imposed on the land by intensive forestry practices, none have evolved in such settings.

Under intensive forestry management, the most vulnerable communities are the unique and biologically rich ones associated with forests older than harvest age (over 20 to 100 years depending on forest type and product; Amaranthus et al. 1994, Franklin et al. 1981, Marcot 1997); hardwoods (because repeated cutting of conifers on short rotation cycles discourages the establishment of these late-successional species); and riparian zones, wetlands, and streams (Gregory et al. 1987, Kuenzler 1989,Thomas 1979).

Changes in Forest Structure

At the stand level, there are three important differences between natural and harvested forest stands: age, size of gap openings, and abundance and distribution of large dead woody debris (Morrison and Swanson 1990, Sharitz et al. 1992, Spies and Franklin 1991). Each of these factors plays a key role in functioning and structure of forest ecosystems.

Clearcutting results in even-aged regeneration of trees, while natural disturbances such as fire and wind can result in uneven-aged regeneration. For example, fire creates different effects on individual trees in a stand depending on temperature, time of day, and position in the burn, and it also influences establishment of seedlings. These variables leave trees of various ages, some partially functioning and others dead, which contribute to the regeneration of the forest and provide microhabitat for many species.

Timber harvesting, especially clearcutting, leaves large swaths of open area. In contrast, natural disturbances create gaps of mixed sizes depending on cause. These can range from a single tree-fall gap to large blowdowns caused by hurricanes and tornadoes. Tornadoes in boreal forests, for example, may create clearings measuring over 100,000 hectares.

Snags or standing dead trees, along with other woody debris, provide important functions in forests (Harmon et al. 1986). Over the long term, of course, they contribute to soil fertility through their decomposition, but in the meantime they serve as important structural elements to prevent erosion and provide habitat for many organisms. Most woodpecker species, for example, nest in cavities they excavate from standing dead trees, and fallen dead trees provide habitat for numerous species, both on land and in streams (Figure 3; McArthur 1989, Sedell et al. 1988).

Forest Fragmentation

Extensive clearcutting has resulted in the fragmentation of many forested ecosystems into smaller patches that have more forest edge exposed to open, cutover habitats (Figure 4; Harris 1984). The effects of such fragmentation on forest remnants include changes in the microclimate (Chen et al. 1995), in species composition, and in species behavior. Changes in species composition may include loss of some species as a result of unsuitable forest micorenvironment, competitive interactions with species at the forest edge, or insufficient total foraging habitat. The change in microclimate at the forest edge may also affect seed dispersal, movement of flying insects, decomposition rates, and size of plant and animal populations.

Forest managers must examine effects of fragmentation on a species-by-species basis with emphasis placed on imperiled species and also "keystones"— species that play a disproportionately vital role in an ecosystem relative to their abundance and whose removal has large ripple effects on other plants and animals as well as on ecological processes. To reduce the impact of timber harvesting on biodiversity,

Photo by Jerry Franklin.

Figure 4 - Timber harvest on federal lands has favored a dispersed patch clearcutting technique in many regions, including the Pacific Northwest. Unfortunately, the technique used resulted in the fragmentation of many landscapes, creating small forest patches, which do not provide intact forest conditions, and immense amounts of edge, which create many problems in maintaining forest stability and diversity. Warm Springs Indian Reservation (previously Mount Hood National Forest), Oregon.

forest management should consider the mosaic of forest patches on the landscape and the connectedness of habitat for forest species in planning future cuts.

Forests managed for timber harvest can be fragmented by roads as well as clearcuts. Roads may affect biodiversity in a number of ways, principally by creating barriers to movement, access routes for predators (including humans), and corridors for invasions by noxious weeds and pathogens (Perry 1988, Small and Hunter 1988). Numerous studies have shown that population sizes of bears, wolves, moose, and mountain lions decline as road density increases (e.g., Brocke et al. 1989).

The spread of both native and exotic pests and pathogens in many forest systems can be linked to simplification and fragmentation of the forest during harvesting, certain replanting practices on clearcuts, and the ready travel corridors provided by extensive road networks. Problems with pathogens and tree-eating insects in forestry have often been associated with widespread planting of a single tree species (Perry 1998). From an ecological standpoint, the strategy with the greatest probability of long-term success in protecting forests against pests and pathogens is to encourage maintenance of a diverse set of controls such as occurs in nature.

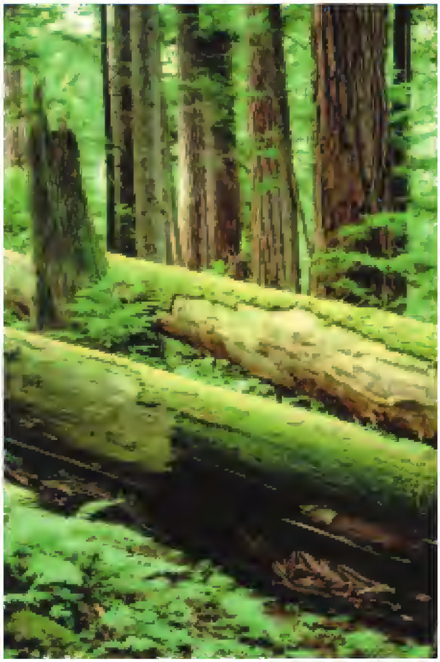


Figure 5 - Interior of old-growth Douglas-fir stand showing the structural complexity of natural forests provided by multiple canopy layers, snags, and fallen logs. Mt. Baker-Snoqualmie National Forest. Photo by Jerry Franklin.

Structural Complexity

Research has demonstrated that structural complexity is an important feature of natural forest ecosystems (e.g., Perry 1994). Vegetation of different heights provides a variety of habitats for the rich diversity of species associated with healthy forests. Tree harvesting usually reduces elements of this structural diversity, including multiple canopy layers, dead snags, and large fallen logs (Figure 5). Ecologists are currently investigating how much structural complexity is necessary and whether forest management practices such as long cutting rotations and variable-retention harvesting (which leaves more live trees, snags, and downed logs on a cutover site) can maintain ecologically important structural features while still allowing timber harvest (Franklin et al. 1997). Despite gaps in our understanding, sustainable forestry strategies should seek to return managed forests to the structure more typical of natural forests in order to assure protection of biodiversity and ecosystem functioning.

Another major research task is to determine what gains in biodiversity actually accrue from retaining mature green trees in perpetuity. Results to date show that young stands with remnant old trees support a greater abundance of some old-growth-associated species than do uniformly young stands, and also sustain some species not found at all in young stands (Hansen et al. 1995, Peck and McCune 1997, Schowalter 1995).

Ecosystems are sensitive to changes in the number and kinds of species found in their communities. Because species can vary dramatically in their contribution to ecosystem functioning, the identity of the species present in a community is important. Declining species richness can lead to deterioration in overall levels of ecosystem functioning. Loss of functional groups or reductions in the number of species that occupy a particular level in the food web (grazers, browsers, predators, decomposers) can also cause declines in ecosystem functioning (Tilman et al. 1997). Two important groups of species in conifer-dominated forests are hardwood trees and shrubs, which are present at one or more stages of succession and are frequently viewed as "weeds." Hardwoods are important because they enhance nutrient cycling, act as biological dams following disturbance, provide unique habitat and food for animals, and modulate fire severity.

LANDSCAPE-LEVEL ISSUES IN FOREST MANAGEMENT PLANNING

While most forestry research has focused on the management of individual stands, most important forest policy issues require consideration of landscape-level phenomena and concerns (see also the Committee of Scientist Report 1999). Sustainable forestry necessitates that individual stands be managed in the context of larger spatial scales. Issues such as regulation of water yields, conservation of biological diversity, and maintenance of aquatic ecosystems require the application of principles from landscape ecology. These principles include concern for size and shape of forest patches, edge effects, and connectivity – that is, the movement of organisms and materials through the landscape. Lack of attention to these landscape-scale concerns in stand-by-stand planning can lead to further habitat fragmentation and cumulative negative effects on forest communities. Indeed, the failure to consider larger landscape

issues underlies policies and practices that have been blamed for repeated over-cutting of National Forest lands. Considerations of spatial pattern are essential in management plans that strive to assure normal ecological functioning within the landscape (Harris 1984, Franklin and Forman 1987).

As an example, consideration of forest patch size and shape and the extent of edge influences is critical in assessing whether the interior forest conditions required by many species are actually present in a landscape. The influence of recently cut areas on adjacent forest patches (edge effects) can be very extensive. For instance, microclimatic influences of a clearcut patch – perhaps greater sunlight, higher temperatures, drying winds — may extend for 10 to 30 meters (with extremes of 200 to 400 meters) into an adjacent old-growth forest patch (e.g., Chen et al. 1993). Edge influences can be so pervasive that a landscape in which 10-hectare patches of cutover and forest are interspersed will entirely lack interior forest conditions after half of the landscape has been harvested (Franklin and Forman 1987).

Recognizing the sensitivity of portions of a landscape is another essential element in landscape planning. *All parts of the landscape are not created equal.* Floodplains, banks, and shallow-water zones associated with streams, rivers, wetlands, lakes and ponds are examples of sensitive areas. Areas of unstable soil provide another example. In many forested mountainous landscapes, soil stability depends substantially upon the root strength of the standing forest; clearcut this forest and the likelihood of landslides increases dramatically. Other sensitive areas in a landscape may be source areas for woody debris and sediments for streams and rivers, rock outcrops and scree slopes, and calving areas for deer, elk, and other ungulates. All of these types of sensitive areas should be recognized and protected as part of landscape-level forest management planning.

Some have proposed that spatial issues can be adequately addressed simply by providing that a certain percentage of each watershed be maintained in a series of four or five structural stages of development (e.g., Oliver et al. 1997). However, proponents of this approach use structural stages that do not adequately represent complex structural development that occurs in natural forest stands, and they often fail to incorporate principles of landscape ecology just discussed. Such simplifications have value in dealing with plantations or intensively managed stands, but not in designing sustainable policies for National Forest lands managed to meet diverse values and goals. The proportion of various forest conditions or stages present in a given landscape should depend upon regional context and management objectives.

GLOBAL CHANGE: IMPLICATIONS FOR FOREST MANAGEMENT

Combustion of fossil fuels, deforestation, and other human activities are contributing to the buildup of carbon dioxide (CO_2) and other so-called greenhouse gases in the atmosphere, a phenomenon expected to drive warming of the global climate. However, one way the earth maintains a balanced atompshere is by storing or "sequestering" carbon (Perry 1994). Forests help mitigate the accumualtion of CO_2 in the atmosphere by absorbing this trace gas from the air to fuel photosynthesis. Half of the carbon absorbed is released back to the atmoshpere during respiration, while the other half is sequestered in soils, sediments, and wood. This makes forests a significant global resevoir for carbon, but it is unknown how much this sequestration will mitigate increasing emissions of CO_2.

Forest responses to a warmer world with increased atmospheric CO_2 are hard to predict. Research on individual plants in controlled settings indicates that a primary effect of rising CO_2 will be enhanced plant growth (DeLucia et al. 1999). However, it is unclear how such findings will translate to ecosystems in the field over time. A changing climate will likely bring not just a shift in temperatures but unpredictable changes in precipitation, cloudiness, disturbance patterns, and perhaps timing of growing seasons (Perry 1994).

Increased tree growth in enriched CO_2 environments would require increased nutrient availability to produce the extra wood, roots, and leaves. Yet there are indications that decomposition and nutrient cycling could be hampered. For example, some research shows plants respond to increased CO_2 and growth by producing leaves and other tissues with lower nitrogen concentrations (Schlesinger 1997). Organic matter low in nitrogen decomposes more slowly, raising the specter of reduced nitrogen availability and constraints on potential increases in plant growth.

A larger scale consequence of altered global climate patterns could be changes in the distribution of species, including the geographic regions suitable for important forest species. Recent predictions for the eastern U.S. suggest, for example, that changes in climate could lead to the complete loss of species such as sugar maple, with its new range lying entirely in Canada. In the central states, a northward shift of loblolly pine populations from Oklahoma, Tennessee and North Carolina to central Illinois and Indiana is predicted, with the southern limit of loblolly pines moving from the Gulf Coast into central Alabama and Georgia (Perry 1994). Such projections raise the question of how quickly plant and animal species will be able to migrate as their suitable climatic range shifts, especially when they must migrate across fragmented, populated, and otherwise human-altered landscapes.

Besides altering the atmosphere and climate, pollution from fossil fuel burning could have direct impacts on forest distribution by raising levels of tropospheric ozone, which accumulates near the Earth's surface. Ozone is a very reactive, short-lived gas that accumulates mainly on hot, stagnant summer days. Ozone damages plants by penetrating the leaf pores (stomata) and oxidizing cell membranes and other structures. The result is a reduction in net photosyn-

thesis that translates into reduced forest growth. According to one estimate, rising ambient ozone levels are currently reducing forest growth in New England by more than 10 percent. Air masses containing high ozone concentrations can travel up to hundreds of kilometers from industrialized regions, affecting forests in relatively remote areas.

Another result of fossil fuel burning is the formation of oxides of sulfur and nitrogen in the atmosphere. Reactions with water vapor transform these oxides to sulfuric and nitric acids, which fall with precipitation as acid rain. As mentioned earlier in this report, dry deposition of nitrogen and acid rain can lead to nitrogen saturation, soil acidification, and detrimental impacts on some forest growth.

Not only are the direct effects of each of these global environmental changes difficult to predict, but forests will experience all of them simultaneously, making projections of future forest growth and health even more difficult. Short-term experiments alone cannot tell us what the long-term effects of these interacting stresses on forests will be. Efforts are underway to develop computer models that simulate effects of these stresses on physiology of trees and allow us to make and test predictions about the future. Unfortunately, we will not be able to validate those predictions, except by watching our uncontrolled global experiments unfold.

Implications for future forest management

Forestry has always had to plan for the long term against a backdrop of rapidly changing social and physical environments. If forest productivity and other forest values are to be sustained in the face of global change, management policies must make unprecedented use of the knowledge base that has been developed on forest ecosystem dynamics and response to disturbance. From a scientific perspective, Forest Service activities should work in concert with other national environmental efforts to monitor changes in the physical and chemical environment over time.

Managers should be particularly alert for the potential of ozone damage to reduce productivity in eastern forests and also for increased nitrate leaching to acidify soils, streams and lakes, a phenomenon now occurring in the Colorado Front Range and California's San Bernardino Mountains as well as in the northeast (Fenn et al. 1998). Given the combined effects of harvest removals and acid deposition in many areas, forest soils should be monitored for impending deficiencies in calcium, magnesium, and potassium. Finally, intervals between timber harvests may need to be lengthened in some forests and whole-tree harvesting techniques reduced in areas where they are now practiced.

Our National Forests, of course, must continue to serve values beyond wood production, including biodiversity conservation and recreational and aesthetic needs. If global changes force plant and animal species to migrate to new regions over the next century, National Forests must be prepared to play an important role by providing relatively continuous and undisturbed corridors through which species can move. And if forest declines at the southern edge of species' ranges require them to migrate, forest managers must be alert to the possibility that human intervention may be needed to help species reach suitable new habitat.

Photo by Ken Hammond, USDA.

Photo by Lori Hidinger.

Figure 6 - Forests on public lands provide many recreation opportunities such as camping, hiking, bird-watching, biking, and horseback riding. They also offer places for quite contemplation and reflection.

POLICY ANALYSIS ASSUMPTIONS AND WHAT WE KNOW ABOUT FOREST ECOSYSTEMS

A number of policy proposals regarding management of the National Forest System have recently been put forward. Most of these proposals have embedded within them assumptions about the workings of forest ecosystems and landscapes. Sometimes such assumptions are explicitly identified, but more often, the underlying assumptions are implicit and invisible to many readers. In this section we have identified some of these assumptions and examined them in light of the current ecological knowledge outlined in the previous section. These

include assumptions about forest stand dynamics, disturbances, landscapes, and our ability to substitute for or replace natural processes with active management programs.

The following analyses consider: 1) value of forest reserves versus intensively managed forests, 2) whether silviculture can substitute for natural forest processes, and 3) the role of timber harvesting in forests managed for ecological values.

NATURAL STAND DYNAMICS, SUCCESSIONAL CHANGE, AND DISTURBANCES: THE ROLE OF FOREST RESERVES

A premise of many policy proposals, such as the Report on Forest Health of the United States (Oliver et al. 1997), is that the internal dynamics of forest stands – that is, natural successional change — and the potential for natural disturbances make it impractical to rely on forest reserves as the centerpiece of programs to maintain biodiversity and other important ecological functions society values on National Forest lands. That is, since forest stands undergo changes in species composition, structure, and functioning during succession, these proposals assert that managers need to provide for periodic cutting and replacement of such stands in order to maintain valued ecological functions. Furthermore, they assume that some natural disturbance such as wildfire, windstorm, insects, or disease will eventually destroy the existing stand and necessitate its replacement anyway.

Thus, many of these proposals call for elimination of reserve status and the return of current reserves within the National Forest system to the pool of intensively managed lands. This would represent a major change in policy, as would the opposite approach: establishment of extensive new areas of reserves. We review here the definition, purpose, and value of this land-use designation and the current debate over whether natural forests are more vulnerable to disturbance than intensively managed forests.

What is a reserve?

Reserves are forests managed primarily to maintain the natural processes and conditions present prior to European settlement. These conditions and processes are recognized as fluctuating within a "range of historic or natural variability." Given the primary emphasis on natural conditions, reserve management typically excludes overt manipulative activities such as timber harvest and road building that introduce direct human influences.

Nevertheless, *forest reserves are managed*. Management can and often does include activities designed to maintain or restore desired conditions or processes. A common example is the use of prescribed fire and/or managed natural wildfire programs to achieve goals related to maintenance of forest conditions (such as early successional pine forests) and processes (especially fire, which has historically been suppressed).

There are many examples of forest reserves being actively and successfully managed to maintain particular forest conditions. Examples include forest areas within Yosemite and Sequoia-Kings Canyon National Parks in California. Fire is a necessary process in these ecosystems, contributing to plant reproduction, nutrient cycling, and habitat creation. In these reserves, forests ranging from the ponderosa pine-oak at lower elevations to lodgepole pine and California red fir at higher elevations are being maintained by a combination of prescribed burning and natural wildfires. Structural complexity and habitat conditions for many forest species are closer to a natural state in these reserved forests than on adjacent forest lands that have been subject to extensive timber harvesting (Sierra Nevada Ecosystem Project 1996).

What purposes do reserves serve?

Biodiversity

Many ecologists believe that the most efficient way to maintain biological diversity is by designating a well-designed system of reserves that encompass an array of ecosystem types and conditions (e.g., Noss et al. 1995). Thus, efforts to conserve biodiversity are often linked to identification and protection of forest reserves. Ecologists agree that a comprehensive system of such lands can probably protect populations of most species, along with much of their genetic diversity and the natural communities in which they occur.

A fundamental question related to current policy debates over the future of reserves, however, is whether biodiversity could be maintained as well as or better in forests that are managed with the primary goal of timber production. This will be considered in more detail in a following section. It is sufficient to note here that by carefully logging a forest—paying close attention to vegetation structure, coarse woody debris, harvest unit patch size and context, and other ecological considerations discussed earlier in this report—it is likely that one could maintain many of the species found in forest reserves.

Providing habitat for any one species of concern to conservationists may well be compatible with harvesting timber. For example, in many southern forests, careful timber management can provide habitat for the endangered red-cockaded woodpecker. Similarly, in the coniferous forests of the Pacific Northwest, sophisticated silvicultural manipulations of managed forest stands under lengthened cutting rotations can, at least hypothetically, provide for northern spotted owls, flying squirrels, and related species (Carey et al. 1996). However, these approaches work because the focus is on one or a relatively few species. Since most forest ecosystems include thousands of species, it is likely that some species would lack adequate or suitable habitat in an intensively managed forest. Explicitly trying to incorporate the requirements of thousands of species into a timber management plan is clearly impossible.

Any reduction of diversity that might occur if all current reserves were returned to intensive management would raise the presently unanswerable question of how much

biodiversity is sufficient to maintain resistance to pests and sustain the capacity of the forest ecosystem to adapt to changing conditions. The extent and functions of biodiversity, especially genetic diversity, at the landscape level are poorly understood at present. Therefore, one very important reason for biologists' emphasis on reserves is the high level of uncertainty associated with providing for adequate biodiversity in managed landscapes. In the Pacific Northwest, biologists were essentially unanimous in choosing the certainty of providing suitable habitat for late-successional, old-growth species in a system of forest reserves over much greater uncertainty associated with growing such habitat as a part of timber management programs (Forest Ecosystem Management Assessment Team 1993, Johnson et al. 1999).

Benchmark Ecosystems

One of the most salient values of biological reserves is to provide benchmarks or controls for research and monitoring programs designed to determine the ecological effects of various forest management practices. An example is the control watersheds used at experimental sites such as Hubbard Brook Experimental Forest in the White Mountain National Forest in New Hampshire and Coweeta Ecological Research Forest in the Southern Appalachians (see Box). Given our current understanding of population, ecosystem and landscape processes, it is clear that such control areas need to be large, well distributed, and representative of the kinds of ecosystems that we are managing. Ecological reserves provide us with a context for evaluating the rest of the landscape that is subject to our manipulation.

Recreational and Aesthetic Values

It is also important to note that other attributes of reserves give them unique value, albeit beyond the purview of ecological science. Many people value reserves for spiritual, aesthetic, and recreational reasons simply because they are places that are not routinely modified by human hands (Figure 6). Maintenance and enhancement of these forest values has clearly become increasingly important to society and a necessary part of sustainable forest management.

Are reserves more vulnerable to natural disturbances?

Two related premises are stated or implicit in some forest proposals: one, that reserves are more vulnerable to natural disturbances than actively managed landscapes; and two, that natural forests are more susceptible to disturbances than managed forests. A corollary is that we can, therefore, create managed forest landscapes that will be less susceptible to disturbance than natural forest landscapes.

There is no evidence to suggest, however, that natural forests are more vulnerable to disturbances than managed forest stands. Indeed, there is considerable evidence to the contrary, evidence that natural forests are actually more resistant to many types of both small- and large-scale disturbances. This is a very complex issue, yet in most cases, the natural landscape proves to have the greater natural resistance to disturbance. We consider here evidence from three types of disturbance: wildfire, windthrow, and pests.

Wildfire

It has been an article of faith in forestry for many decades that a managed landscape is less susceptible to wildfire than a wild landscape. Indeed, conversion of old-growth forests in the Pacific Northwest has sometimes been justified on grounds that it reduced the potential for catastrophic fire. Scientific investigation has shown that, of all of the forest ages and conditions, unmanaged old-growth forests in this region are least likely to burn catastrophically. The resistance of such forests to fire is related to a variety of factors, including the cool, moist, windless microclimate characteristic of old-growth forests. Old growth forests do contain immense fuel loads, and when they do burn, fire suppression may be very difficult. This is the source of their bad reputation with foresters because in the early part of the twentieth century, policy required forest managers to fight fires in these forests. Essentially all of the large catastrophic fires in Pacific coastal old-growth forests during the last half of the nineteenth and first half of the twentieth century were of human origin. For example, the famous Yacholt Burn of 1902 in Washington and the Tillamook Burn of 1933 in Oregon originated outside of massive old-

The Coweeta Ecological Research Forest

Coweeta Long-Term Ecological Research Forest, located in the southern Appalachian mountains of the eastern U.S., is one example of a natural ecosystem where scientists conduct ecological research on scales ranging from years to decades. Studies at this 5,397-acre facility focus on the responses of forest ecosystems to natural and human-induced disturbances. Within this landscape, scientists witness the effects of experimental manipulations on scales ranging from forest stands to entire watersheds. Studies include continuing analyses of long-term hydrology, nutrient cycling, and productivity in response to management practices and natural disturbances (drought, flood, wind, insects); the cumulative effects of land-use practices on water quality; assessment of prescribed burning effects on the forest environment; implementation of ecosystem management on National Forests; impacts of forest litter on stream productivity, decomposition, and food webs; forest ecosystem response to atmospheric nitrogen deposition; physiological studies of forest carbon balance and competition; and biodiversity. The long-term data from these experimental programs are invaluable to scientists, land managers and decision-makers alike.

growth forests and spread into them under very dry and windy conditions.

Some of the greatest wildfire risks and most difficult fire-control situations occur in landscapes that contain intimate mixtures of both young forests—either managed or natural— and old-growth forests. Young stands are more likely to burn than old-growth stands, particularly if the young stands result from earlier wildfires and incorporate large amounts of dead fuel from earlier stands. If the young stands are the result of regrowth after timber harvest, human access to the region is likely to have been dramatically increased by road construction, and this has mixed consequences: it provides improved access for fire suppression, but it greatly increases the chances of both accidental and intentional human ignitions, which are now the most important source of ignitions in many forests. Some landscape models suggest the concept of mixed landscape is risky (e.g., Franklin and Foreman 1987). These models are supported by empirical evidence from fires in southwestern Oregon and northern California in which cutover areas with young coniferous stands burned catastrophically while intervening residual old-growth forest patches experienced reduced fire intensities and partial or complete survival (Perry 1998).

Windthrow

In some forest regions in the West, evidence indicates managed landscapes containing mixtures of forest conditions and age classes—including high contrast edges where forest stands meet cutover patches—are more vulnerable to catastrophic windthrow than natural landscapes. For example, a massive blowdown in Oregon's Bull Run River watershed in the early 1980s was primarily a result of dispersed-patch clearcutting and resulting high contrast edges between cutovers and roads and residual old-growth forest stands (Franklin and Forman 1987). In the case of hurricane damage in the Northeast, however, older stands, especially mature white pine forests, are at higher risk of blowdown.

Insects and Disease

Managed landscapes may also create conditions that are more favorable for outbreaks of insect pests and disease. For example, the creation of large pine plantations in the southeastern United States has provided optimal conditions for large-scale outbreaks of the southern pine beetle. The fact that managed landscapes tend to be less diverse and provide large contiguous blocks of one or a few susceptible species and age classes makes catastrophic outbreaks of many pathogens more likely. In contrast, however, the older spruce stands in the Canadian boreal forests are most susceptible to spruce budworm outbreaks. In this case, it may be that management efforts to reduce natural disturbance maintain these spruce forests beyond their "natural" life span.

Summary

There is no easily generalized evidence that a managed landscape will be more resistant to catastrophic disturbance than a natural landscape. Since forest managers and researchers both have had limited success in predicting the occurrence of catastrophic events much before they occur, it is not practical to attempt to preempt the role of natural disturbances by harvesting stands prior to their occurrence.

SUBSTITUTING SILVICULTURE FOR NATURAL FOREST PROCESSES

One implicit assumption in some analyses and policy proposals is that management of forest stands by silvicultural manipulation can fully substitute for natural forest processes in maintaining the full ecological values of forests. This includes substituting management practices for the effects of the natural disturbances and successional changes in forests over decades to centuries.

Duplicating natural disturbance processes

A tenet of forestry for many decades has been that regeneration harvest techniques are modeled on, and essentially mimic, natural disturbance processes. For example, it is commonly stated that clearcutting is comparable to the destruction of a forest stand by wildfire. In light of current ecological knowledge, we consider here whether it is justified to assume that timber harvest practices can duplicate and substitute for the effects of natural disturbance.

Consider first what we know about the character of natural forest disturbance processes. It is useful to recognize two broad classes of disturbance: *chronic* disturbances, which are of moderate intensity and produce low to moderate levels of mortality of existing dominant trees; and *catastrophic* disturbances, which result in death of the majority of existing dominant trees and regeneration of a new tree cohort. It is necessary to consider both types of disturbance since they have different implications for management potential and problems.

Chronic disturbance

Forests subject to frequent, light- to moderate-intensity disturbances tend to absorb the effects of the disturbances and incorporate them into the basic fabric of the stand. Examples include forests subject to repeated fires of light to moderate intensity, such as the pine forests of interior western North America, and forests subject to frequent gap-scale wind disturbances, such as many of those found in the Northeast. Such disturbance patterns create and maintain structurally complex forests with multiple canopy layers and uneven tree ages over large areas for long periods of time. Ecologically, these forests are mosaics of small structural units. While location of individual structural types changes over time, the forest as a mosaic is stable (Bormann and Likens 1979).

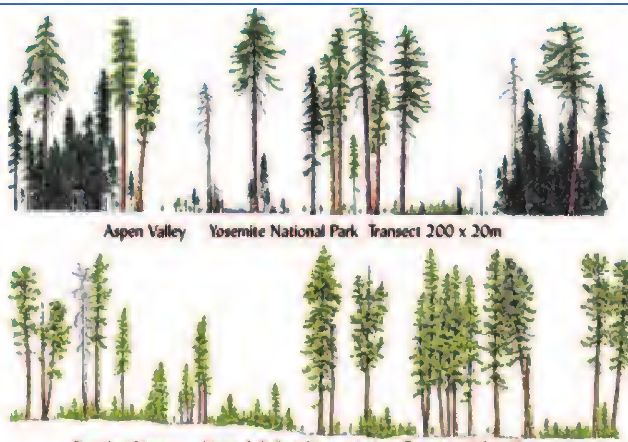


Figure 7 - Two cross-sections of forest stands (mixed conifer and ponderosa pine) showing the mosaic of small patches of contrasting structural conditions which are maintained by chronic disturbance. Drawings by Robert Van Pelt.

Typically in such ecosystems, late-successional forests permanently occupy very large percentages of the landscape. While individual patches are dynamic, the forest as a whole is very stable since it is rarely subject to a large-scale catastrophic disturbance. Traditionally, we have failed to appreciate the stability of such late-successional forest ecosystems. These stands are often characterized as very "dynamic" and "unstable" because each of the small structural patches is seen as a "stand" rather than being recognized as part of a stand mosaic. The pine and mixed-conifer forests of the interior Columbia Basin and the Sierra Nevada range of California provide excellent examples of this. These forests were naturally subjected to frequent light- to moderate-intensity wildfire, which produced complex late-successional forest mosaics consisting of small patches of contrasting structural conditions (Figure 7). These conditions dominated pre-settlement landscapes. In the case of Sierra Nevada mixed-conifer forests, it is estimated that these complex, late-successional forests occupied more than 80 percent of the pre-settlement landscape.

Rather than a destabilizing force, wildfire plays a critical role in maintaining such landscapes. Indeed, some tree species depend on natural fire for regeneration. For example, some plants produce seeds that are released or are able to germinate only after being exposed to the high temperatures or smoke that accompany fires. Jack pine and lodgepole pine have cones that do not open without the heat of a fire. Other trees such as the giant sequoia require an ash bed created by intense ground fires for successful seedling germination. The Eastern white pine, red pine, ponderosa pine, black spruce, and yellow birch regenerate and grow best when fires burn away competing understory vegetation and surface organic material.

Eastern deciduous forests provide an example of late-successional, structurally complex forests that are maintained by chronic disturbances such as wind and ice storms. These disturbances create small openings in the forests resulting in a fine-scale mosaic of structural patches that collectively make up ecologically functional stands.

Catastrophic disturbances

In forests subject to infrequent, catastrophic disturbances, the forest develops through a sequence of gradual changes in structure and often species composition until a major disturbance abruptly destroys the stand and triggers its regeneration. There are many examples of this type of pattern in different parts of the world. For example, the Douglas fir-western hemlock forests of the Pacific Northwest are subject to infrequent but intense wildfires (Agee 1993). At Mount Rainier National Park in Washington, for example, nearly half the forest was affected by a major fire in the late fifteenth century (Hemstrom and Franklin 1982, Franklin et al. 1986). Many forests subject to this catastrophic disturbance pattern are characterized by shade-intolerant, pioneering species, which are believed to depend upon such disturbances for successful regeneration.

Biological legacies

It is a common misconception that natural forest disturbances kill most of the living organisms and consume or remove most of the organic matter. Both chronic and catastrophic disturbances leave behind very large legacies of surviving organisms, organic matter, and complex landscape patterns—*biological legacies* (Figure 8). Extraordinary legacies, both biological and structural, survive almost all catastrophic disturbances. These legacies include living organisms—often mature, reproductive-age living trees—and propagules, as well as organic matter, much of it in the form of large standing dead and downed trees and boles. Large

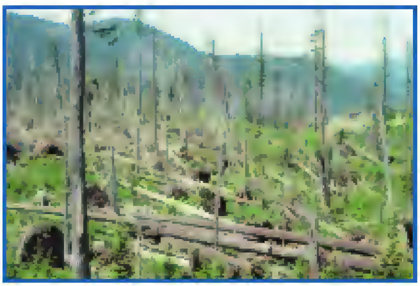
organic structures, whether living or dead, provide habitat for many organisms and are the food source for myriad belowground organisms, including those critical to decomposition and nutrient cycling. Legacies often persist also in the form of complex vegetation patterns because of the heterogeneity of disturbances such as fire and windthrow. The exact nature of biological legacies is obviously very much dependent upon the characteristics of the disturbance.

Studies of ecological recovery following the 1980 eruptions of Mount St. Helens highlighted the importance of biological legacies. Rather than functioning as a single disturbance, the volcanic eruptions actually produced a complex of intense, geographically widespread, and overlapping disturbances (Franklin et al. 1988). Researchers found that ecological recovery processes at Mount St. Helens were initially dominated by biological legacies such as buried root stocks, surviving plants, and wind-dispersed seeds from adjacent slopes (Franklin 1990, Frenzen et al. 1986), and these legacies continue to be important factors in both the nature and rate of ecological recovery.

A simulated hurricane blowdown at Harvard Forest was conducted to mimic the effects of a 1938 hurricane. The outcome was a tremendous change in the structure of the forest, with the majority of the green leaves now located near the forest floor. Many of the pulled-over trees leafed out the following spring and only died after two or three years. This result, combined with advanced regeneration and sprouting of new vegetation, resulted in a fairly closed canopy. Nitrogen mineralization in the soil, trace gas fluxes, nitrification and nitrate losses were unaffected, even though the stand looked decimated.

Different types of disturbance vary dramatically in the nature and consequences of their biological legacies. This can be illustrated by comparing intense wildfire and windstorm events with clearcutting (Figure 9). Fires tend to kill the forest from below so that the largest trees are most likely to survive while small trees such as seedlings and saplings are killed; many standing dead trees remain, along with smaller initial amounts of downed woody debris. Windstorms, on the other hand, tend to kill the largest trees and leave the understory, including tree seedlings and saplings, largely undisturbed; most structural legacies are in the form of boles blown onto the forest floor. Clearcuts leave very little in the way of structural or biological legacies since all trees and wood are typically removed or burned.

Biological legacies of the types outlined here are very important in ecosystem recovery processes. For example, surviving trees and other plants act as lifeboats for invertebrates, vertebrates, and fungal species. Many organisms can survive intense catastrophic disturbances provided their habitat—that is, trees and logs—and food sources still exist. These surviving organisms then help to regenerate the forest



(a) Biological legacies from a large blowdown in Mount Hood National Forest include an immense amount of woody debris, snags, and some residual green trees which survive. The forest floor, shrub, and herb layers, plus seedlings to regenerate the canopy, remain intact. All of the carbon is retained on site.

(b) Biological legacies left after a wildfire in Yosemite National Park, CA include standing dead trees and down wood. Depending on the intensity of the fire, much of the carbon can be consumed in the burn.

(c) A 90-year-old Douglas-fir stand that regenerated after the 1902 Yacholt Burn in southern Washington. It contains a scattered legacy of large, old-growth trees which survived (those projecting above the canopy of the younger trees). These legacy old-growth trees create a structurally diverse stand which supports spotted owls.

Figure 8 - Biological legacies include living and dead trees and down logs left after disturbance. Photos by Jerry Franklin.

Biological legacy	Wildfire	Windstorm	Clearcut
Large living trees	Few	Few	None
Snags	Abundant	Common	None
Down logs	Common	Abundant	Few
Intact tree regeneration	No	Yes	No

Figure 9 - Biological legacies associated with different types of intense disturbances. Natural disturbances leave more biological legacies to foster the regeneration of the forest than do clearcuts.

community. Also, structural legacies such as live trees, standing dead trees, and logs on the forest floor provide much greater structural richness than would otherwise be present if only new seedlings covered a site.

Substituting harvest for natural disturbance

Biological legacies of natural disturbances and their ecological effects emphasize the sharp contrasts between natural disturbance and intensive timber harvesting. Traditional even-aged managed forests and harvest cutting methods leave little, if any, woody structure behind as a biological legacy. Living organic legacies also tend to be fewer because of intensity and thoroughness of clearcutting and associated site management practices.

It is possible to modify silvicultural practices to incorporate much higher levels of biological legacies and to emulate more closely natural disturbance processes (Franklin et al. 1997). The modifications involve retaining elements of the harvested stands, such as live trees, snags, and downed logs (Figure 10). This approach, sometimes known as the "variable retention harvest system," has been adopted on federal lands in the Pacific Northwest, as well as on public and private forest lands in British Columbia.

Various mechanical, chemical, thermal, and other ecological effects of specific disturbances also need to be considered when contrasting natural disturbances with timber harvesting. Many disturbances have very distinctive and ecologically important effects. For example, fire has a unique role in forest ecosystems due to heating and thermal consumption of organic materials, volatilization of organic nitrogen, and mineralization of other nutrients that occur. These effects cannot be duplicated simply by cutting and removing trees.

Wind also creates major mechanical effects on a forest caused by uprooting of trees and mixing of soil. On forested sites subject to rising ground water levels after tree loss, the mechanical effects of uprooting may be critical to maintaining productive forest conditions. One example of this is seen in northern hardwood forests in New England where a study demonstrated that differences in nitrate leaching between harvested and uncut stands are still detectable 100 years after harvest. Differences in species composition persist as well.

ECOLOGICAL ROLE OF TIMBER HARVESTING IN MANAGEMENT OF FORESTS FOR ECOLOGICAL VALUES

Proposals to ban commercial logging, such as that supported by the Sierra Club and proposed as the National Forest Protection and Restoration Act of 1999 (McKinney 1999), would represent a significant departure from the long-standing mandate of the National Forest System. Clearly there are many economic and social arguments that could be mustered against this proposition. Less obvious are some ecological issues that argue against eliminating logging from all of our National Forest lands.

Habitat for early successional species

An implicit assumption of such a proposal is that habitat for species in need of early successional habitats can always be maintained through natural disturbances. Many species require early successional habitat, and in some regions this forest stage has become rather uncommon, jeopardizing the viability of certain species populations. National Forest managers should have the option of creating habitat for such species by logging a forest and thus setting back successional development. For example, in Florida's Ocala National Forest, managers clearcut the forest in huge blocks to provide habitat for the endangered Florida scrub jay, a species that requires large patches of scrub. In theory, the species' needs could be met by catastrophic crown fires; in reality, natural crown fires are too rare to provide sufficient habitat for the scrub jay population. Seeking permission to set such fires would be politically futile.

While the justification for logging to create habitat is clearest with endangered species, this argument can also be extended to the many game species that use early successional ecosystems. Public demand for sizable populations of

these game species is another reason for forest managers to keep logging in their toolbox.

Fuel control

In many types of forests, ground fires ignited by lightning historically reduced fuel loads and thus diminished the likelihood of catastrophic crown fires. Unfortunately, it is not always feasible for forest managers to emulate this natural fire pattern and minimize fire hazards through controlled burns. For example, proximity to roads and houses often makes it very difficult to set fires safely. In dry ponderosa pine forests of the interior West, 80 years of fire exclusion have allowed fuels to accumulate in some areas to the point that it may be difficult or impossible to keep "controlled" ground fires from spreading and killing overstory trees. Under such circumstances, it may be desirable for forest managers to reduce fuel loads by cutting and removing trees.

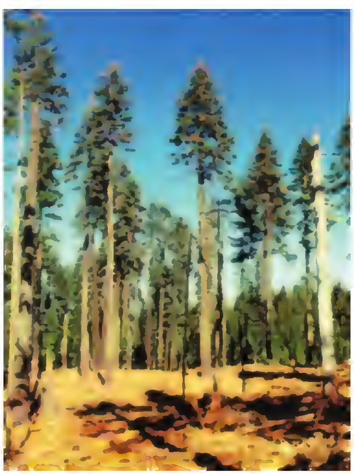
Restoration ecology and forest health

Many forests have been degraded by human activities and no longer have a desirable structure and composition. Judicious use of logging can accelerate the process of restoring these forests to a more natural state. In some cases, tree removal strategies to protect forests from insect and disease epidemics are also necessary. For example, in 1996, National Forest lands contained more than 5,800 individual southern pine beetle infestations. To prevent further spread of this forest-degrading pest, certain "cut and remove" and "cut and leave" tactics were implemented as control measures. The Caney Creek Wilderness of the Ouachita National Forest in Arkansas had seven pine beetle infestations within the wilderness that required control to prevent further spreading. Reducing forest stress through application of good forest management practices can help minimize losses to pests and other conditions that debilitate forests. The challenge in restoring forest health is to fix one set of problems without creating new ones.

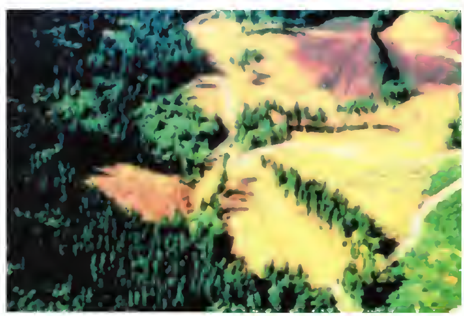
CONCLUSIONS

Managing our National Forests to provide for diverse values has always been a challenge, and the task looms ever larger as society demands more wood along with more recreational opportunities and more sensitive stewardship of forest ecosystems. In a period when conflicting social expectations are forcing a reevaluation of management policies, it is not surprising to see radical proposals being proffered. This report has pointed out the ecological weaknesses of some of the more prominent of these proposals.

Meeting the diverse and changing demands of society for the goods and services that forests provide certainly requires creativity and flexibility, and we do not wish to stifle innovation. Ultimately, however, sustainable forest management must be science-based. Forest policies must view the forest as a complex ecosystem and consider the long-term and broad-scale implications of management actions. Almost all simple proposals to improve management of our National Forests will be inadequate for one reason: our National Forests are too complex for simple solutions. Easy answers are almost always wrong because of the immense variability among forest types and regions as well as differences in the social and economic context of each forest. Such complexity and its attendant uncertainty may leave some managers reluctant to act, yet it is neither necessary nor realistic to



(a) Harvesting with permanent retention of large-diameter trees throughout the harvest unit (ground view of partial cut stand). Plumas National Forest, California.



(b) Harvest unit with 15% of the forest permanently retained in aggregates: strips and blocks of the original forest (aerial view of clearcut with strips of retained forest) Plum Creek Timber Company land, southwestern Washington.

Figure 10 - Variable harvest retention, an alternative to clearcutting, leaves behind structures, such as large old trees, to lifeboat diversity and structurally enrich the new stand. Photos by Jerry Franklin.

suspend management. Complexity and uncertainty, however, do demand conservative approaches to management of our natural resources. These realities also necessitate management plans that are forthright about the level of existing knowledge and the uncertainty and risk associated with alternative proposals. Creative, thoughtful policies based on valid scientific assumptions will help us move toward better long-term stewardship of our National Forests.

ACKNOWLEDGMENTS

The Panel would like to thank all who contributed to the completion of this report. Specifically we would like to thank David Tilman and anonymous reviewers for their comments on the manuscript; Yvonne Baskin for "making it sing"; Faith Kearns for layout and design; and the *Annual Review of Ecology and Systematics* for allowing us to present a synthesis of ideas from the David Perry (1998) article published by them. Special thanks to The Pew Charitable Trusts for supporting the development, printing, and distribution of this document through a grant to the Ecological Society of America (Grant Number: 1997-003192). The opinions expressed in this report are those of the authors and do not necessarily reflect the views of The Pew Charitable Trusts.

SUGGESTED READINGS

Aber, J.D. 1992. Nitrogen cycling and nitrogen saturation in temperate forest ecosystems. Trends in Ecology and Evolution. 7: 220-223.

Agee, J. K. 1993. Fire ecology of Pacific Northwest forests. 493 p. Island Press: Washington, DC.

Amaranthus, M.P, J.M. Trappe, L. Bednar, D. Arthur. 1994. Hypogeous fungal production in mature Douglas-fir forest fragments and surrounding plantations and its relation to coarse woody debris and animal mycophagy. Canadian Journal of Forestry Research 24:2157-65.

Bormann, F. H., and G. E. Likens. 1979. Pattern and process in a forested watershed. 253 p. Springer-Verlag: New York, NY.

Brocke, R.H, J.P. O'Pezio, K.A.A. Gustafson. 1989. A forest management scheme for mitigating impact of road networks on sensitive wildlife species. Is Forest Fragmentation A Management Issue in the Northeast? USFS NE Forest Experiment Station General Technical Report NE-140. Washington, DC. USGPO.

Burger, J.A. and W.L. Pritchett. 1988. Site preparation effects on soil moisture and available nutrients in a pine plantation in the Florida flatwoods. Forestry Science 34:77-87.

Carey, A. B., C. Elliott, B. R. Lippke, et al. 1996. Washington forest landscape management project – a pragmatic, ecological approach to small-landscape management. Washington State Department of Natural Resources Washington Forest Landscape Management Project Report No. 2, 99 p. Olympia, WA.

Chen, J., J.F. Franklin, and T.A. Spies. 1995. Growing season microclimatic gradients from clearcut edges into old-growth Douglas-fir forests. Ecological Applications 5(1):74-86.

Chen, J., J. F. Franklin, and T. A. Spies. 1993. An empirical model for predicting diurnal air-temperature gradients from edge into old-growth Douglas-fir forest. Ecological Modeling 67:179-198.

Cole, D.W. 1995. Soil nutrient supply in natural and managed forests. Plant Soil. 168-69:43-53.

Committee of Scientists Report. 1999. Sustaining the People's Lands. Recommendations for Stewardship of the National Forests and Grasslands into the Next Century. USDA, Washington, DC.

DeLucia, E.H., J.G. Hamilton, S.L. Naidu, R.B. Thomas, J.A. Andrews, A. Finzi, M. Lavine, R. Matamala, J.E. Mohan, G.R. Hendrey, and W.H. Schlesinger. 1999. Science 284: 1177-1179.

Doran, J.W. and T.B. Parkin. 1994. Defining and assessing soil quality. In: Doran, J.W., D.C. Coleman, D.F. Bezkicek, and B.A. Stewart (eds.). 1994. Defining Soil Quality for a Sustainable Environment. Soil Sci. Soc. Am. Spec. Pub. No. 35. Madison, WI. pp. 3-21.

Federer, C.A., J.W. Hornbeck, L.M. Tritton, C.W. Martin, R.S. Pierce and C.T. Smith. 1989. Long-term depletion of calcium and other nutrients in eastern us forests. Environmental Management. 13: 593-601.

Fedkiw, J. 1999. Managing Multiple Uses on National Forests, 1905-1995: A 90-year learning experience an it isn't finished yet. USDA Forest Service FS-628. Washington, DC.

Fenn, M.E., M.A. Poth, J.D. Aber, J.S. Baron, B.T. Bormann, D.W. Johnson, A.D. Lemly, S.G. McNulty, D.F. Ryan and R. Stottlemyer. 1997. Nitrogen excess in North American ecosystems: predisposing factors, ecosystem responses and management strategies. Ecological Applications. 8: 706-733.

Forest Ecosystem Management Assessment Team. 1993. Forest ecosystem management: an ecological, economic, and social assessment. Various pagination. USDA Forest Service, Portland, OR.

Franklin, J.F., D.R. Berg, D.A. Thornburg, J.C. Tappeiner. 1997. Alternative silvicultural approaches to timber harvesting: variable retention harvest systems. In Kohm, K.A. and J.F. Franklin (eds) 1997. Creating a Forestry for the 21st Century. Washington, DC: Island Press. pp111-39.

Franklin, J.F. 1990. Biological legacies: a critical management concept from Mt. St. Helens. pp. 215-219. In: McCabe, R.E., ed. Transactions of the Fifty-fifth North American Wildlife and Natural Resources Conference. March 16-21, 1990; Denver, CO. Washington, DC: Wildlife Management Institute: 55.

Franklin, J. F., P. M. Frenzen and F. J. Swanson. 1988. Recreation of ecosystems at Mt. St. Helens: contrasts in artificial and natural approaches. Pages 1-37. In: Rehabilitating Damaged Ecosystems. Volume II. J. Cairns Jr. Boca Raton, FL, Chemical Rubber Co.

Franklin, J. F., W. H. Moir, M. A. Hemstrom, S. E. Greene, and B. G. Smith. 1986. The forest communities of Mount Rainier National Park. USDI National Park Service Monograph Series No. 19.

Franklin, J. F., and R. T. T. Forman. 1987. Creating landscape pattern by forest cutting: ecological consequences and principles. Landscape Ecology 1:5-18.

Franklin, J.F., K. Cromack, Jr. W. Denison, A. McKee, C. Master, et al. 1981. Ecological characteristics of old-growth Douglas-fir forests. USDA Forest Service General Technical Report PNW-118. Portland, OR.

Frenzen, P.M., J.E. Means, J.F. Franklin, C.W. Kiilsgaard, W.A. McKee, and F.J. Swanson. 1986. Five Years of Plant Succession on Eleven Major Surface Types Affected by the 1980 Eruptions of Mount St. Helens, Washington IN: Keller, S.A.C., (editor), 1986, Mount St. Helens: Five Years Later: Eastern Washington University Press, Cheney, Washington, 441p., ISBN 0-910055-09-2.

Gregory, S.V., G.A. Lamberti, D.C. Erman, K.V. Koski, M.L. Murphy, J.R. Sedell. 1987. Influences of forest practices on aquatic production. In Salo, E.O. and T.W. Cundy (eds) 1987. Streamside Management: Forestry and Fisheries Interactions, Contribution No. 57, Institute of Forest Resources, University of Washington, Seattle, WA. pp233-55.

Hansen, A.J, C. McComb, R. Vega, M.G. Raphael, M Hunter. 1995. Bird habitat relationships in natural and managed forests in the west Cascades of Oregon. Ecological Applications 5:555-69.

Harmon, M.E., J.F. Franklin, F.J. Swanson, P. Sollins, S.V. Gregory et al. 1986. Ecology of coarse woody debris in temperate ecosystems. Adv. Ecol. Res. 15:133-302.

Harr, R.D. 1976. Hydrology of small forest streams in western Oregon. General Technical Report PNW-55. U.S. Forest Service Pacific Northwest Experimental Station. Portland, OR.

Harr, R.D., W.C. Harper, J.T. Krygier, F.S. Hsieh. 1975. Changes in storm hydrographs after road building and clear-cutting in Oregon Coast Range. Water Resources Research 11:436-44.

Harris, L. D. 1984. The fragmented forest. 211 p. University of Chicago Press: Chicago, IL.

Hemstrom, M. A., and J. F. Franklin. 1982. Fire and other disturbances of the forests in Mount Rainier National Park. Quaternary Research 18:32-51.

Hibbert, A.R. 1969. Water yield changes after converting a forested catchment to grass. Water Resources Research. 5: 634-640.

Hornbeck, J.W., C.W. Martin, R.S. Pierce, F.H. Bormann, G.E. Likens and J.S. Eaton. 1986. Clearcutting northern hardwoods: effects on hydrologic and nutrient ion budgets. Forest Science. 32: 667-686

Johnson, D.W. 1992. Effects of forest management on soil carbon storage. Water, Air, Soil Pollution 64:83-120.

Johnson, D.W. and D.E. Todd. 1987. Nutrient export by leaching and whole-tree harvesting in a loblolly pine and mixed oak forest. Plant Soil 102, 99-109.

Johnson, K. N, F. Swanson, M. Herring, and S. Greene. 1999. Bioregional assessments. Science at the crossroads of management and policy. 398 p. Island Press: Washington, DC.

Jones, J.A. and G.E. Grant. 1996. Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon. Water Resources Research. 32(4): 959-974. (HJA pub# : 1529).

Kimmins, J.P. 1977. Evaluation of the consequences for future tree productivity of the loss of nutrients in whole-tree harvest. Forest Ecol. and Manage. 1, 169-183.

Kohm, K.A., and J. F. Franklin, eds. 1997. *Creating a forestry for the 21st century*. Island Press, Washington, DC.

Kuenzler, E.J. 1989. Value of forested wetlands as filters for sediments and nutrients. In Hook, D.D. and R. Lea. 1989. Proc. Symposium: The Forested Wetlands of the Southern United States, USDA Forest Service General Technical Report SE-50. Asheville, NC. pp 85-96.

Likens, G.E., F.H. Bormann, N.M. Johnson, D.W. Fisher and R.S. Pierce. 1970. Effects of forest cutting and herbicide treatment on nutrient budgets in the Hubbard Brook watershed-ecosystem. Ecological Monographs. 40: 23-47

Marcot, B.G. 1997. Biodiversity of old forests of the west: a lesson from our elders. pp 87-105.

McArthur, J.V. 1989. Aquatic and terrestrial linkages: flood plain functions. In Hook, D.D. and R. Lea. 1989. Proc. Symposium: The Forested Wetlands of the Southern United States, USDA Forest Service General Technical Report SE-50. Asheville, NC. pp 107-16.

McKinney, C. 1999. H.R. 1396. National Forest Protection and Restoration Act of 1999. U.S. House of Representatives. Introduced 4/13/99.

Morrison, P.H. and F.J. Swanson. 1990. Fire History and Pattern in a Cascade Mountain Landscape. USDA Forest Service General Technical Report PNB-GTR-254. Portland, OR.

Noss, R.F., E.T. LaRoe III, J.M Scott. 1995. Endangered Ecosystems of the U.S.: a Preliminary Assessment of Loss and Degradation. Biological Report 28. Washington, DC. USDI National Biological Service.

Oliver, C., D. Adams, T. Bonnicksen, J. Bowyer, F. Cubbage, N. Sampson, S. Schlarbaum, R. Whaley, and H. Wiant. 1997. Report on Forest Health of the United States by the Forest Health Science Panel. Panel chartered by Charles Taylor, member, U.S. Congress, 11th District, North Carolina.

Peck, J.E. and B.M. McCune. 1997. Remnant trees and canopy lichen communities in western Oregon: a retrospective approach. Ecological Applications 7:1181-87.

Perry, D.A. 1998. The Scientific Basis of Forestry. Annual Review of Ecology and Systematics. 29: 435-466. (HJA pub# : 2568).

Perry, D.A. 1994. Forest Ecosystems. The Johns Hopkins Press. Baltimore, MD.

Perry, D. A. and S.L. Rose. 1988. Productivity of forest lands as affected by site preparation. In: Powers, R.; Robson, T., eds. Proceedings of the California Conference on Forest Tree Nutrition and Soil Fertility; 1981 March 23; Lake Tahoe, CA. Gen. Tech. Rep. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station: (HJA pub# : 991).

Perry, D.A. 1988. Landscape patterns and forest pests. Northern Environmental Jouranl 4:213-28.

Powers RF, DH Alban, RE Miller, AE Tiarks, CG Wells et al. 1990. Sustaining site productivity in North American forests: problems and prospects. In SP Gessel, DS Lacate, GF Weetman, RF Powers (eds) Sustained Productivity of Forest Soils, Proc. 7th North American Forest Soils Conference. Univ. British Columbia Faculty of Forestry. Vancouver. p 49-79.

Reiter M.L. and R.L. Beschta 1995. Effects of forest practices on water. In Cumulative Effects of Forest Practices in Oregon. Report for Oregon Department of Forestry. Chapter 7, R.L. Beschta, J.R. Boyle, C.C. Chambers, W.P. Gibson, S.V. Gregory, et al. Salem, OR.

Schlesinger, W.H. 1997. Biogeochemistry: An Analysis of Global Change. Academic Press, New York.

Schowalter, T.D. 1995. Canopy arthropod community response to forest age and alternative harvest practices in western Oregon. Forest Ecology Management 78:115-25.

Schulze, E.D. 1989. Air pollution and forest decline in a spruce (*Picea abies*) forest. Science. 244: 776-783.

Sedell, J.R., P.A. Bison, F.J. Swanson, S.V. Gregory (eds.) 1988. What we know about large trees taht fall into streams and rivers. USDA Forest Service General Technical Report PNW-GTR-229. Portland, OR.

Sharitz, R.R., L.R. Boring, D.H. Van Lear, J.E. Pinder III. 1992. Integrating ecological concepts with natural resource management of southern forests. Ecological Applications 2:226-37.

Sierra Nevada Ecosystem Project. 1996. Status of the Sierra Nevada. Volume II. Assessments and scientific basis for management options. Univ. California Wildland Resources Center Report No. 37. 1528 p.

Small, M.F. and M.L. Hunter. 1988. Forest fragmentation and avian nest predation in forested landscapes. Oecologia 76:62-64.

Smith, CT Jr., ML McCormack Jr., JW Hornbeck, and CW Martin. 1986. nutrient and biomass removals from red spruce—balsam fir whole-tree harvest. can. J. For. res. 16, 381-388.

Spies, T.A. and J.F. Franklin. 1991. The structure of natural young, mature, and old-growth Douglas-fir stands in western Oregon and Washington. In Ruggerio, L.F., K.B. Aubrey, A.B. Carey, M.H Huff (eds).

Wildlife and Vegetation of Unmanaged Douglas-Fir Forests. USDA Forest Service General Technical Report PNW-GTR-285. Portland, OR.

Swanson, FJ. JL Clayton, WF Megahan, G Bush. 1989. Erosional processes and long-term site productivity. In: Perry, D. A.; Meurisse, R.; Thomas, B. [and others], eds. Maintaining the long-term productivity of Pacific Northwest forest ecosystems. Portland, OR: Timber Press: 67-81. (HJA pub# : 1009).

Thomas, J.W. (ed). 1979. Wildlife Habitats in Managed Forests of the Blue Mountains of Oregon and Washington. USDA Forest Service Agricultural Handbook No. 553. Washington, DC.

Tilman, D., J. Knops, D. Wedin, P. Reich, M. Ritchie, and E. Sieman. 1997. The influence of functional diversity and composition on ecosystem processes. Science 277: 1300-1302.

USDA NRCS. United States Department of Agriculture Natural Resources Conservation Service. 1996. Indicators for soil quality evaluation. Soil Quality Information Sheet. U.S. Department of Agriculture, Washington, DC.

Wiersum, K.F. 1995. 200 years of sustainability in forestry: lessons from history. Environmental Management 19:321-29.

About the Panel of Scientists

This report presents the thoughts of a panel of scientists chosen to include a broad array of expertise. The affiliations of the members of the panel of scientists are:

Dr. John Aber, Complex Systems Research Center, E.O.S., University of New Hampshire, Durham, NH 03824

Dr. Norman Christensen, Nicholas School of the Environment, Duke University, Durham, NC 27708-0328

Dr. Ivan Fernandez, Department of Applied Ecology and Environmental Sciences, University of Maine, Orono, ME 04469

Dr. Jerry Franklin, College of Forest Resources, University of Washington, Seattle, WA 98195-0001

Ms. Lori Hidinger, Sustainable Biosphere Initiative, Ecological Society of America, Washington, DC 20006

Dr. Malcolm Hunter, Department of Wildlife Ecology, University of Maine, Orono, ME 04469-5755

Dr. James MacMahon, Department of Biology, Utah State University, Logan, UT 84322-0001

Dr. David Mladenoff, Department of Forest Ecology Management, University of Wisconsin, Madison, WI 53706

Dr. John Pastor, Natural Resources Research Institute, University of Minnesota, Duluth, MN 55811

Dr. David Perry, Oregon State University, Corvallis, OR

Mr. Ron Slangen, Sustainable Biosphere Initiative, Ecological Society of America, Washington, DC 20006.

Dr. Helga Van Miegroet, Department of Forest Resources, Utah State University, Logan, UT 94322-5215

About the Science Writer

Yvonne Baskin, a science writer, edited the report of the panel of scientists to allow it to more effectively communicate its findings with non-scientists.

About Issues in Ecology

Issues in Ecology is designed to report, in language understandable by non-scientists, the consensus of a panel of scientific experts on issues relevant to the environment. *Issues in Ecology* is supported by a Pew Scholars in Conservation Biology grant to David Tilman and by the Ecological Society of America. All reports undergo peer review and must be approved by the editorial board before publication.

Previous Reports

Previous *Issues in Ecology* reports available from the Ecological Society of America include:

Vitousek, P.M., J. Aber, R.W. Howarth, G.E. Likens, P.A. Matson, D.W. Schindler, W.H. Schlesinger, and G.D. Tilman. 1997. Human Alteration of the Global Nitrogen Cycle: Causes and Consequences, *Issues in Ecology* No. 1.

Daily, G.C., S. Alexander, P.R. Ehrlich, L. Goulder, J. Lubchenco, P.A. Matson, H.A. Mooney, S. Postel, S.H. Schneider, D. Tilman, and G.M. Woodwell. 1997. Ecosystem Services: Benefits Supplied to Human Societies by Natural Ecosystems, *Issues in Ecology* No. 2.

Carpenter, S., N. Caraco, D. L. Correll, R. W. Howarth, A. N. Sharpley, and V. H. Smith. 1998. Nonpoint Pollution of Surface Waters with Phosphorus and Nitrogen, *Issues in Ecology* No. 3.

Naeem, S., F.S. Chapin III, R. Costanza, P.R. Ehrlich, F.B. Golley, D.U. Hooper, J.H. Lawton, R.V. O'Neill, H.A. Mooney, O.E. Sala, A.J. Symstad, and D. Tilman. 1999. Biodiversity and Ecosystem Functioning: Maintaining Natural Life Support Processes, *Issues in Ecology* No. 4.

Mack, R., D. Simberloff, W. M. Lonsdale, H. Evans, M. Clout, and F. Bazzaz. 2000. Biotic Invasions: Causes, Epidemiology, Global Consequences and Control, *Issues in Ecology* No. 5.

Additional Copies

To receive additional copies of this report ($3 each) or previous *Issues in Ecology*, please contact:

Ecological Society of America
1707 H Street, NW, Suite 400
Washington, DC 20006
(202) 833-8773, esahq@esa.org

The *Issues in Ecology* series is also available electronically at http://esa.sdsc.edu/.

About Issues in Ecology

Issues in Ecology is designed to report, in language understandable by non-scientists, the consensus of a panel of scientific experts on issues relevant to the environment. *Issues in Ecology* is supported by the Pew Scholars in Conservation Biology program and by the Ecological Society of America. It is published at irregular intervals, as reports are completed. All reports undergo peer review and must be approved by the Editorial Board before publication.

Issues in Ecology is an official publication of the Ecological Society of America, the nation's leading professional society of ecologists. Founded in 1915, ESA seeks to promote the responsible application of ecological principles to the solution of environmental problems. For more information, contact the Ecological Society of America, 1707 H Street, NW, Suite 400, Washington, DC, 20006. ISSN 1092-8987

esa